

TITIM GIS-tool: A GIS-based decision support system for measuring the territorial impact of transport infrastructures

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ARTICLE INFO

Article history:

Available online 2 June 2014

Keywords:

GIS-based decision support system
Territorial impacts
Linear transport infrastructure
Accessibility improvements
Landscape connectivity

ABSTRACT

To achieve sustainability in the area of transport we need to view the decision-making process as a whole and consider all the most important socio-economic and environmental aspects involved. Improvements in transport infrastructures have a positive impact on regional development and significant repercussions on the economy, as well as affecting a large number of ecological processes.

This article presents a DSS to assess the territorial effects of new linear transport infrastructures based on the use of GIS. The TITIM – Transport Infrastructure Territorial Impact Measurement – GIS tool allows these effects to be calculated by evaluating the improvement in accessibility, loss of landscape connectivity, and the impact on other local territorial variables such as landscape quality, biodiversity and land-use quality. The TITIM GIS tool assesses these variables automatically, simply by entering the required inputs, and thus avoiding the manual reiteration and execution of these multiple processes. TITIM allows researchers to use their own GIS databases as inputs, in contrast with other tools that use official or predefined maps.

The TITIM GIS-tool is tested by application to six HSR projects in the Spanish Strategic Transport and Infrastructure Plan 2005–2020 (PEIT). The tool creates all 65 possible combinations of these projects, which will be the real test scenarios. For each one, the tool calculates the accessibility improvement, the landscape connectivity loss, and the impact on the landscape, biodiversity and land-use quality. The results reveal which of the HSR projects causes the greatest benefit to the transport system, any potential synergies that exist, and help define a priority for implementing the infrastructures in the plan.

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1. Introduction

Determining the effects of a planned linear transport infrastructure (road and railway) is a highly complex task. There are a large number of environmental and socio-economic aspects involved, and a consensus has yet to be reached as to how to assess both the positive and negative impacts.

Transport infrastructures are a vital social and economic resource, and provide access to today's economic and social opportunities (Richardson, 2005). Investment in the construction and maintenance of transport infrastructures is vast, and its repercussions can be seen throughout all areas of society (Hilden, Furman, & Kaljonen, 2004; Short & Kopp, 2005). This is why correct planning of transport systems is essential (Hilden et al., 2004).

The increased use of transport systems has gone hand-in-hand with a growing awareness of their impacts (Hine, 1998), creating a need for sustainable and integrated development (European commission, 1998; US department of transportation, 2000). To attain sustainability in the area of transport it is necessary to have an overall view of the decision-making process; in other words, all the aspects involved – transport planning, land use and the environment – must be considered in conjunction rather than viewed in isolation. For Hull (2005) the great challenge is to succeed in integrating these principles into decisions on transport and land use.

This challenge requires tools that can identify and assess the environmental, social and economic aspects of their decisions (Abaza & Baranzini, 2002; Boulanger & Bréchet, 2005). A further requirement is to be able to identify which criteria need to be assessed, the importance of each one and how they can be integrated; this is a highly challenging task (Boulanger & Bréchet, 2005). To facilitate this process, the European Parliament passed Directive 2001/42/EC on the assessment of the effects of certain

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plans and programmes on the environment. Strategic Environmental Assessment (SEA)¹ is the ideal tool for complying with this Directive, as it includes social and economic aspects alongside environmental concerns. The SEA must be applied flexibly, but its application must identify sustainability targets, criteria and indicators; identify and compare alternatives and impacts (scoping); and assess these impacts (Arce & Gullón, 2000; Retief, 2007; Thérivel & Partidario, 1996).

It is far from simple to identify the most important aspects requiring consideration. Scientists and planners broadly agree on a number of options: from the socio-economic point of view, the improvement in accessibility to goods and services has a positive impact on regional development (Ozbay, Ozmen-Ertekin, & Berechman, 2003; Vickerman, Spiekermann, & Wegener, 1999). In various planning documents at the European or national scale – the European Spatial Development Perspective (ESDP) (European commission, 1999), the recommendations for the development of trans-European transport networks (TEN-T) (European commission, 2005) and the Strategic Infrastructures and Transport Plan 2005–2020 (Ministerio de Fomento, 2005) – the term “accessibility” is cited as a priority objective, and is considered an instrument for achieving economic and social cohesion targets. Likewise, several studies (Geurs & van Wee, 2004; Gutiérrez, Monzón, & Piñero, 1998; Halden, 2003; Monzón, Ortega, & López, 2013; Ortega, López, & Monzón, 2012; Talen & Anselin, 1996 among others) defend the need to exploit the potential of accessibility indicators as a support tool in infrastructure planning tasks aimed at efficiency and territorial cohesion.

Regarding territorial environmental aspects, linear transport infrastructures divide ecosystems, thus leading to a loss of habitats and increased fragmentation (McGarigal, Romme, Crist, & Roworth, 2001; Reed, Johnson-Barnard, & Baker, 1996). Habitat fragmentation can be seen as a loss of connectivity (Serrano, Sanz, Puig, & Pons, 2002) between habitats, which hinders the displacements of organisms, energy flows and migratory and dispersive movements between different patches (Taylor, Fahrig, Henein, & Merriam, 1993; Tischendorf & Fahrig, 2001).

In addition to this loss of connectivity, transport infrastructures have a considerable impact on the territory due to the occupation of the space by part of the infrastructure itself, and to their use (traffic); these are common to all types of linear infrastructures (Geneletti, 2006). The occupation of territory by a new infrastructure brings a decline in the natural values found in it. It is worth highlighting particularly the loss of natural land uses or land with high productivity, the loss of individuals and the resulting loss of biodiversity (Bottero, Comino, Duriavig, Ferretti, & Pomarico, 2013), and the deterioration of the visual landscape (Zube, Sell, & Taylor, 1982).

After establishing the criteria for assessing the effects of infrastructure plans, the next step is to find a tool capable of handling the large volume of quantitative and qualitative geographic data required. The complex interrelationships among the variables (environmental, social and economic) involved in the planning process makes it difficult to reach an objective decision. According to Witlox (2005), the large quantity of data and the complexity of these relationships mean that planners are unable to resolve correctly the problem in hand and must use computers and Information Technology (IT) programmes capable of analysing all the information. The IT tools that have proved to be capable of carrying out this work are GIS, as they are able to handle two types of information: spatial data and the quantitative and/or quantitative

information associated with them. The possibility of making calculations with greater accuracy and objectivity renders this best possible tool for the processes of territorial planning and assessing the impacts caused by transport infrastructures (Sikder, 2009).

There are a number of GIS-based methodologies for solving transport problems. Transport planning is usually related to network analysis. The best route calculations, best activity location, demand models and accessibility calculations are all based on GIS network analysis. Ortega, Mancebo, and Otero (2011) provide a complete description of the GIS process for calculating accessibility indicators at the planning level; Karou and Hull (2014) model the accessibility impacts of changes in public transport provisions; Novak and Sullivan (2014) evaluate accessibility to emergency services via a road network using a link-focused approach; Sadeghi-Niaraki, Varshosaz, Kim, and Jung (2011) study relevant and related variables affecting each road segment during network analysis in order to develop an appropriate impedance model in route planning. Other widely studied aspects concern the environmental impacts of transportation. Demirel, Sertel, Kaya, and Seker (2008) estimate vehicle emissions and determine the impact of traffic on urban air quality using GIS capabilities. García-Montero, López, Monzón, and Otero (2010) develop a methodology to estimate the potential overall impact of an infrastructure plan on biodiversity and global warming for a whole country. Several methodological approaches map areas of transport sensitivity to establish the necessary protection measures (Enei, Münier, Ricci, & Fuglsang, 2012). Other studies seek to optimise the choice of corridors, usually based on spatial multi-criteria analysis, as in De Luca, Dell'Acqua, and Lamberti (2012) for high speed railway (HRS) lines, or Effat and Hassan (2013) for highway routes, considering environmental impacts, social and economical components and cost/geometric factors.

However most of these methodologies are complex and require a long calculation time. They can be improved by decision support systems (DSS), which are capable of storing, handling and processing large quantities of data; they include mathematical models; and they enable the incorporation of multi-attribute decision-making methods. There are DSS for estimating emissions, such as STEEDS (Brand, Mattarelli, Moon, & Wolfier Calvo, 2002), which assess energy and environmental impacts (emissions, pollutants, global warming potential...); or more recently HERA (Sobrinho, Monzon, & Hernandez, 2014), which assess and compare the energy and carbon footprint of different highways and traffic-flow scenarios. In the optimisation of infrastructure routes or location models, DSS evaluate several possibilities for proposed routes. Kim, Wunneburger, Neuman, and Young (2014) evaluate different HSR routes, considering both suitability and cost (construction and land acquisition) aspects; SABILOC (Fernandes, Captivo, & Climaco, 2014) facilitates the problem of location by considering environmental impacts; and Krichen, Faiz, Tlili, and Tej (2014) propose a tool for solving the problem of vehicle routing by means of loading and distance requirements. On the topic of environmental impact assessment, Herrero-Jiménez (2012) identifies environmental impacts based on graphic overlapping between project and environmental factors. However, in contrast with the vast number of GIS methodologies, there are only a limited number of real GIS-based DSS in transport planning.

Most of these DSS compare alternatives or policy options (Brand et al., 2002; Kim et al., 2014; Sobrinho et al., 2014). Some focus on developing complete MCA modules (Coutinho-Rodrigues, Simão, & Antunes, 2011), while others calculate complex indicators, generally emissions-related (Arampatzis, Kiranoudis, Scaloubacas, & Assimacopoulos, 2004; Brand et al., 2002; Sobrinho et al., 2014). However, except in certain cases such as SABILOC (Fernandes et al., 2014), they do not tend to involve very complex GIS calculation methodologies. Specifically, there are no DSS that allow both

¹ Sadler and Verheem (1996) define Strategic Environmental Assessment (SEA) as “a systematic process for evaluating the environmental consequences of proposed policy, plan or programme initiatives in order to ensure they are fully included and appropriately addressed at the earliest appropriate stage of decision making”.

the calculation of complex indicators and the comparison of alternatives to assist in evaluating the effects of new linear transport infrastructures at the planning/national scale, and integrating major territorial, socio-economic and environmental aspects such as improvements in accessibility (Novak & Sullivan, 2014), habitat fragmentation and loss of natural values.

The aim of this article is to contribute to advancing this research topic by providing a GIS-based tool. The TITIM – Transport Infrastructure Territorial Impact Measurement – GIS tool is useful in the early stages of the decision-making process at the strategic level, and helps to determine the most suitable combinations of alternatives (greatest socio-economic benefit and lowest environmental impact). The methodology for assessing the territorial effects of linear transport infrastructure plans is based on the evaluation of the improvement in accessibility, loss of landscape connectivity, and the impact on other local territorial variables such as landscape quality, biodiversity and land-use quality. The tool assesses these variables automatically, simply by entering the required inputs, thus avoiding the need to manually run the large number of processes required.

The next section describes the methodological approach used in this paper to calculate these aspects – integrated in a GIS – and the creation and structure of the TITIM GIS-tool decision support system (DSS). The tool is tested in a case study in Section 3. Finally, Section 4 contains the conclusions.

2. Methodology for the creation and structure of the TITIM GIS-tool

The decision support system (DSS) was developed based on the GIS, using the GIS ArcInfo Workstation and ArcGIS Desktop (Arc-Map). These are two independent but mutually compatible programs. The whole of the process necessary for calculating the selected indicators was programmed in the Arc Macro Language (AML).

The TITIM GIS-tool is structured similarly to a DSS, and formed by a minimum of four modules: a *database*, a series of *mathematical models*, an *inference engine* and a *user interface* (Arampatzis et al., 2004; Brand et al., 2002; Herrero-Jiménez, 2012; Sikder, 2009; Tsamboulas & Mikroudis, 2006). According to the various authors, other elements can be added to these basic elements to design the DSS.

The general structure of the DSS is based on several independent modules that must be run successively to calculate each indicator. The reasons for proceeding in this way instead of with a single module are as follows:

- Only one or several indicators can be calculated. All the potential impacts of the infrastructures have a significance in themselves, and it may thus be interesting for the user to know only some of them.
- As the whole process takes a long time to run, it was considered safer to divide it into several stages to avoid any possible interruptions.
- It offers a greater chance to verify the correct functioning of the expert system, as the results of the different modules can be checked at intermediate stages in the calculation.
- It is easier to incorporate new impacts or modify existing ones.
- The calculation of the indicators requires a whole series of variables to be entered. If this can be done in several stages it is not necessary to have them all available at the start of the process.

The general diagram of the expert system is shown in Fig. 1. It comprises a *scenarios generator module*, *calculation modules*, *calculation module launchers* and an *integration module*. Each one has a

database, a set of mathematical models, an inference engine and a user interface.

2.1. Scenarios generator module

This module allows the creation of all the possible infrastructure combinations in order to analyse different corridor alternatives for the new infrastructures, compare several corridors, and determine which ones contribute the most to the transport system (greatest socio-economic benefit and lowest environmental impact).

The resulting number of combinations will be (Eq. (1)):

$$C = 2^n \quad (1)$$

where C is the number of combinations and n is the number of corridors/alternatives.

It also creates a table for entering the results obtained after calculating the indicators in all the combinations or scenarios.

An infrastructure GIS layer is required to generate the scenarios. Each corridor or alternative considered must be identified by a code in the layer's database.

2.2. Impact calculation modules

A module has been created to calculate each of the variables considered. Each module uses the GIS methodology to calculate a scenario described below. The expert system does not allow them to be run independently, but only with the calculation module launcher described in Section 2.3.

Due to their importance in transport planning, accessibility and landscape connectivity are the main variables selected to assess the effects of infrastructures on the territory (see Fig. 1). The impact on other local territorial variables such as landscape, biodiversity and land-use quality can also be evaluated. We therefore describe the indicators selected to assess each variable, and the method for calculating them by means of Geographic Information Systems (GIS).

2.2.1. Accessibility module

The accessibility indicators are calculated from the displacement time over a transport network.² This network must contain information on the typology and corresponding speed of each section.

All the networks – road, conventional railway and HSR – are considered to be independent. Population centres – the origins and destinations – and stations are also independent. The networks are integrated with population centres and stations as follows: the population centres are displaced to the nearest road, using a snapping GIS tool. The stations are also displaced to the nearest road. The railway lines then need to be displaced to coincide with the stations. Finally the road, conventional railway and HSR networks are linked together to create the network nodes. The change of transport modes occurs at the railway stations.

The pathway is calculated with the minimum displacement time between the municipalities. Travel time is equal to the sum of the times of the arcs travelled along the pathway with the lowest of all possible displacement times, according to Dijkstra's algorithm (1959). The generalised travel time comprises both rail travel time and travel time by road from the origin to the nearest station, and from the station nearest the destination to the actual destination. A detailed description of the generalised travel time

² It is vital for this network to be topologically correct; that is, there must be no connectivity errors between the different arcs composing it, no duplication of elements, and no sections without destinations.

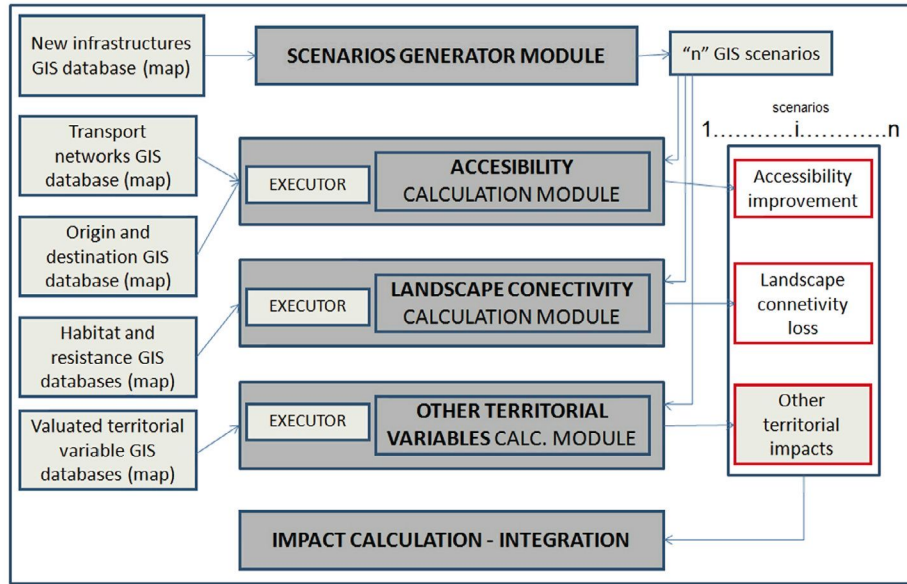


Fig. 1. General diagram of the TITIM GIS-tool.

calculation is given in López (2007) and Ortega (2009). The GIS calculation process is shown in detail in Ortega et al. (2011).

The accessibility value for each node on the network is calculated from the database containing the times (real and ideal) for all the relations, taking into account the opportunities at the destination (how attractive it is for individuals to reach the destination which will allow them to satisfy their needs).

The following indicators are calculated (Table 1).

The following information is needed for the calculation.

A GIS layer including origins and destinations; value of the destination attraction variable in the origins and destinations database, such as population; rail and road GIS layer with information about the typology and speed of each arc in their databases; and station GIS layer.

Either the rail or road transport mode can be selected. In the case of selecting rail, roads are necessary for complementary travel.

2.2.2. Landscape connectivity module

The connectivity of the territory or landscape is calculated based on "displacement cost distance models (Adriaenssens et al., 2003; Gurrutxaga, Lozano, & del Barrio, 2010). The model

calculates the accumulated cost of crossing each cell between the origin and destination, taking into account the friction involved in travelling through the cell due to the cost measurement (slope, impacts, barriers, etc.).

In order to find a connectivity value for each cell of the habitat in the territory, the following connectivity index (CI) was used (Mancebo Quintana, Martín Ramos, Casermeiro Martínez, & Otero Pastor, 2010). CI determines the effective distance of displacement between patches of the same habitat, which is inversely proportional to the displacement cost distances between each origin and its destinations (Eq. (2)).

$$CI_i = \frac{\sum_{j=1}^n \frac{A_j}{de_{ij}}}{2\pi de_{\max}} \quad (2)$$

where:

CI_i is the value of the connectivity index for starting point i .

de_{ij} is the effective distance between starting point i and destination j .

A_j is the area of each cell of the n destinations j that belong to the same class of habitat as starting point i .

Table 1

Accessibility indicators selected (Geurs & Ritsema Van Eck, 2001; Gutiérrez et al., 1998; Kwan, 1998; Ortega et al., 2011; Ortega et al., 2012; Reggiani, 1998).

Type	Indicator	Equation	Description
Potential	Potential accessibility indicator	$PA_i = \sum_j \frac{P_j}{t_{ij}}$ P_j is the population in the destination t_{ij} is the real travel time between the starting point and the destination	It measures the number of opportunities offered by a territory. It takes into account destination size (attraction) and travel cost, considering that the attraction of a destination increases with size and decreases with the cost of travel
Cost	Locational accessibility index	$LA_i = \sum_j t_{ij} \cdot w_{ij}$ t_{ij} is the real travel time. w_{ij} is the weight measuring the destination attraction	It measures the average "time cost" to access these opportunities. The results of these indicators are influenced by the geographical position
Efficiency	Efficiency indicator – Speed	$ESA_i = V_{\max} \frac{\sum_j t_{ij} \cdot w_{ij}}{\sum_j t_{ij} \cdot w_{ij}}$ V_{\max} is the maximum speed T_{ij} is the ideal travel time between the starting point and the destination. The time travelling in a straight line. t_{ij} is the real travel time. w_{ij} is the weight measuring the destination attraction	It measures the average "effective speed": the speed at which the distance between the starting point and the destinations is actually covered. It measures the efficiency of the displacement in function of the quality of the available infrastructure
	Network efficiency gravitational indicator	$EA_i = \sum_j \frac{t_{ij}}{T_{ij}} \cdot w_{ij}$ t_{ij} is the real travel time. T_{ij} is the ideal travel time. w_{ij} is the weight measuring the destination attraction	It also measures the efficiency of displacement in function of the quality of the available infrastructure. In this case, it measures the average "time efficiency"

$2\pi de_{\max}$ is the maximum possible value of the numerator. It is a normalisation factor.

The index reflects the area occupied by each habitat plus its connectivity, as the effective distance takes into account the resistance offered by the landscape matrix to the movement of species (Mancebo Quintana et al., 2010). The distances are calculated for each cell pair in the same habitat. A detailed description of the methodology is given in Ortega (2009).

It must be calculated using the following information.

A raster habitat map; a study area GIS layer; a resistance map, representing the resistance of the territory to the movement of the organisms; number of cells to add in the resistance habitat map (in order to accelerate calculations); raster artificial areas map; GIS table assigning an impedance value to each artificial area type; definition of a maximum connectivity area between similar habitats.

2.2.3. Other territorial variables module

The methodology for analysing other territorial variables consists of determining the quality of the area affected by the planned new infrastructures and delimiting a buffer zone. This requires the creation of quantified maps, as the area is weighted with the corresponding values of the territorial variables considered.

The impact of the infrastructure can be assessed using three methods.

Buffer type: the impact of transport infrastructure is considered to affect an area of influence of the track, but does not decrease as a function of distance.

Curve type: the impact is considered to be inversely proportional to distance. In this case, an impact value corresponding to the distance from the infrastructure is needed.

Linear type: the impact is assessed as linear metres of infrastructure.

Fig. 2 shows the area of influence of a new linear transport infrastructure with the three methods. Left: the area of influence of the infrastructure does not decrease as a function of distance; centre: the impact decreases as a function of distance from the infrastructure; and right: the impact is limited to the infrastructure layout.

Table 2

Methods considered for assessing the impact on other territorial variables.

Type	Buffer type	Curve type	Linear type
Equation	$I = \sum Ap \cdot c$	$I = \sum Ap \cdot f(d, c)$	$I = \sum L \cdot c$

I is the impact value.

Ap is the pixel area in the maps.

c is the quality value assigned to each pixel of the territorial variables (landscape, biodiversity, land-use...) quantified maps.

$f(d, c)$ is a function relating impact with distance to the infrastructure.

L is the length of each type of landscape or land use affected.

The total impact of the transport infrastructure is measured following the equations shown in Table 2.

It must be calculated using the following information.

A raster map showing the values of the selected territorial variable (in order to avoid calculation problems, the value must be an integer); definition of impact method: linear, buffer or curve.

The buffer method requires the impact distance to be defined. If the curve method is selected, a table is needed with the impact value corresponding to the distance from the infrastructure.

2.3. Calculation module launchers

This makes it possible to calculate the impact on all the scenarios previously created by the *scenarios generator* module. The result will be a table or a layer with its associated table, depending on each case.

It also aggregates the results in order to produce a single impact value and allow the subsequent comparison of different scenarios. The following values are aggregated in each case.

2.3.1. Aggregation of accessibility values

This is the sum of all the values of the accessibility indicator for all the municipalities weighted by their population.

2.3.2. Aggregation of connectivity values

The value of each scenario is the average of the values of all the cells.

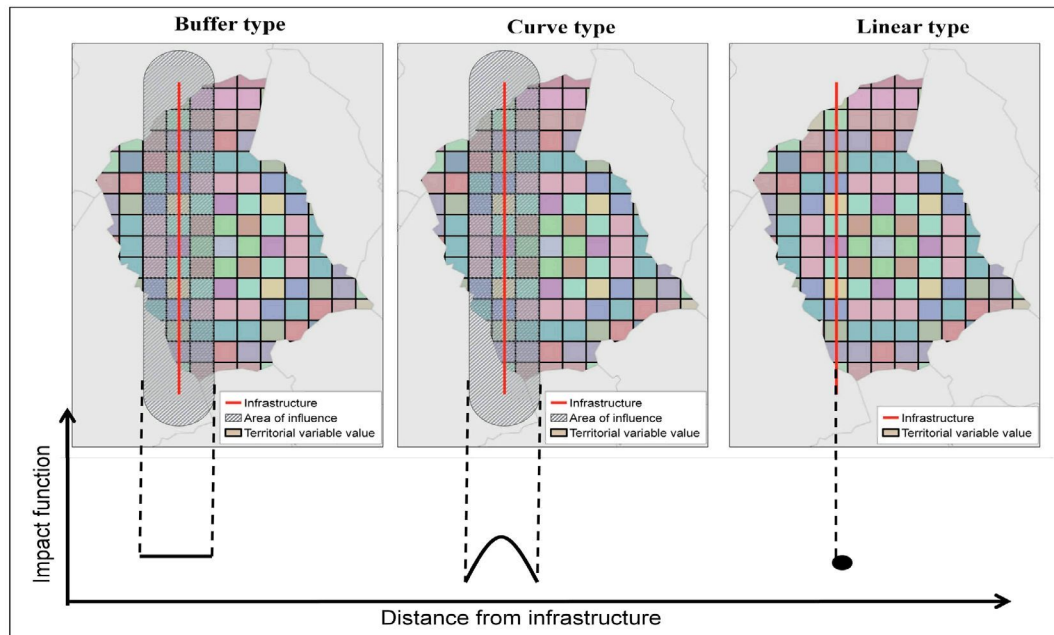


Fig. 2. Impact function of the infrastructure with the three methods.

2.3.3. Aggregation the values of other territorial variables

The value for each scenario is the sum of the values of the territorial variable of all the pixels considered to be affected by the infrastructure.

2.4. Integration module

Finally, the integration module calculates the impact of all reference scenarios, according to Eq. (3).

$$A_i \text{ Change (\%)} = \frac{A_{i0} - A_{if}}{A_{i0}} \times 100 \quad (3)$$

where:

A_{i0} is the value of the indicator in the reference scenario.

A_{if} is the value of indicator in the final scenario.

Similarly, a comparison of the value obtained in a scenario with the value of the “Plan scenario” reveals how much that scenario contributes to the plan as a whole.

Using the multi-attribute method (Malczewski, 1999), the integration module combines the values for all the indicators to obtain a single global impact value according to Eq. (4).

$$U_s = \sum_i x_i \cdot u_{si} \quad (4)$$

where:

U_s is the final value of the s scenario.

x_i is the weight assigned weight to the i variable.

u_{si} is the i variable value in the s scenario.

The integration is done in different phases. The first phase aggregates complementary variables such as landscape connectivity and biodiversity loss, which explain interrelated phenomena (environmental effects). A further phase integrates the variables that are not so closely related. To calculate the Equation, the user needs to define a relative weight for the variables.

3. Case study. Application to new HSR investments

This section contains an example of the application of the TITIM GIS-tool and an analysis of the results. The infrastructures under consideration are six HSR projects in the Spanish Strategic Transport and Infrastructure Plan 2005–2020 (PEIT) (Ministerio de Fomento, 2005).

The objective set by this plan is that the rail system will progressively become the central element in the articulation of inter-modal transport services for both passengers and freight. To achieve this target an important number of HSR projects are currently in the planning stage, with a commercial speed of nearly 220 km/h.

The analysis of several corridors can determine which one brings the maximum benefit to the transport system. In addition, the study of their combinations highlights the potential synergies that may exist. All this enables a priority to be defined for implementing the different infrastructures scheduled in the plan.

3.1. Scenarios generation

First, two basic scenarios are created. The “do-nothing scenario” represents the infrastructures in the base year of the plan, and the “Plan scenario” includes the construction of all the infrastructures planned. Then six HSR corridors are selected from among the ones in the PEIT for the creation of other scenarios. The TITIM will come up with all the possible combinations of these corridors, which will

be used as the actual test scenarios. Fig. 3 shows the selected corridors.

The final number of scenarios is 65. Six are formed by the “do-nothing scenario” plus one corridor; 15 are the “do-nothing scenario” plus two corridors; 20 the “do-nothing scenario” plus three corridors; 15 the “do-nothing scenario” plus four corridors; six the “do-nothing scenario” plus five corridors; one the “do-nothing scenario” plus six corridors and the last two are the “do-nothing scenario” and the “Plan scenario”.

The impact caused by each scenario has been calculated as a percentage compared to the “do-nothing scenario” and per kilometre of infrastructure. The percentage value is considered more important, as the corridors must be completely built in order to be able to achieve the objectives set out in the plan.

3.2. Accessibility improvements

In order to calculate accessibility values, a dense rail (1000 arcs) and road network (89,000 arcs) was modelled with the support of a GIS. The length, estimated speed according to type and the resulting travel time for each arc on the road and railway network were also recorded. The information on the location of the stations and frequency of service used to calculate the travel times was noted. The accessibility values are calculated for all Spanish mainland municipalities, totalling nearly 8110. All the destinations considered for the calculation of the accessibility value for each origin are also Spanish mainland municipalities.

The value of the accessibility indicators was calculated in the scenarios considered, and the indicator *ESA* was selected (see Table 1) as representing the average “effective speed” (Ortega et al., 2011).

Independently, the corridor generating the greatest improvement in average accessibility levels in the whole territory is corridor 1 (scenario 1), with an improvement over the “do-nothing” scenario of 5.97%. When considering scenarios formed by two or more corridors – depending on the corridors that form a scenario – the improvement in accessibility can be seen either at the national level or restricted to the corridor. Fig. 4 shows that scenario 8 spreads the improvement in accessibility (11.76%) around the whole of the territory, whereas the improvements caused by scenario 20 (4.30%) are limited to the area around the corridor.

Table 3 shows the accessibility value, value per kilometre, percentage improvement compared to the “do-nothing scenario” and the order within the scenarios with the same number of corridors.

In the scenarios formed by two corridors, the percentages of improvement are very different. Some scenarios provide more than 50% improvement in accessibility compared to other scenarios. As the number of corridors increases, these differences between scenarios are reduced, as the effects of the corridors on the scenarios is progressively compensated. It is worth highlighting that scenario 46, – the lowest-scoring scenario with four corridors – is surpassed by five scenarios with three corridors (scenarios 27, 22, 33, 29 and 24).

3.3. Landscape connectivity loss

The origins and destinations have been considered to be the habitats existing on the Iberian peninsula on the habitats map of the Ministry of the Environment (DGBIO, 2005), prepared according to Directive 92/43/EEC (The council of the European communities, 1992). The network of infrastructures in the “do-nothing scenario” has been incorporated into this map.

To create an impedance map, a cost value or resistance was assigned to each element in the territory (Martín Ramos, Ortega Pérez, Mancebo Quintana, & Otero Pastor, 2008).

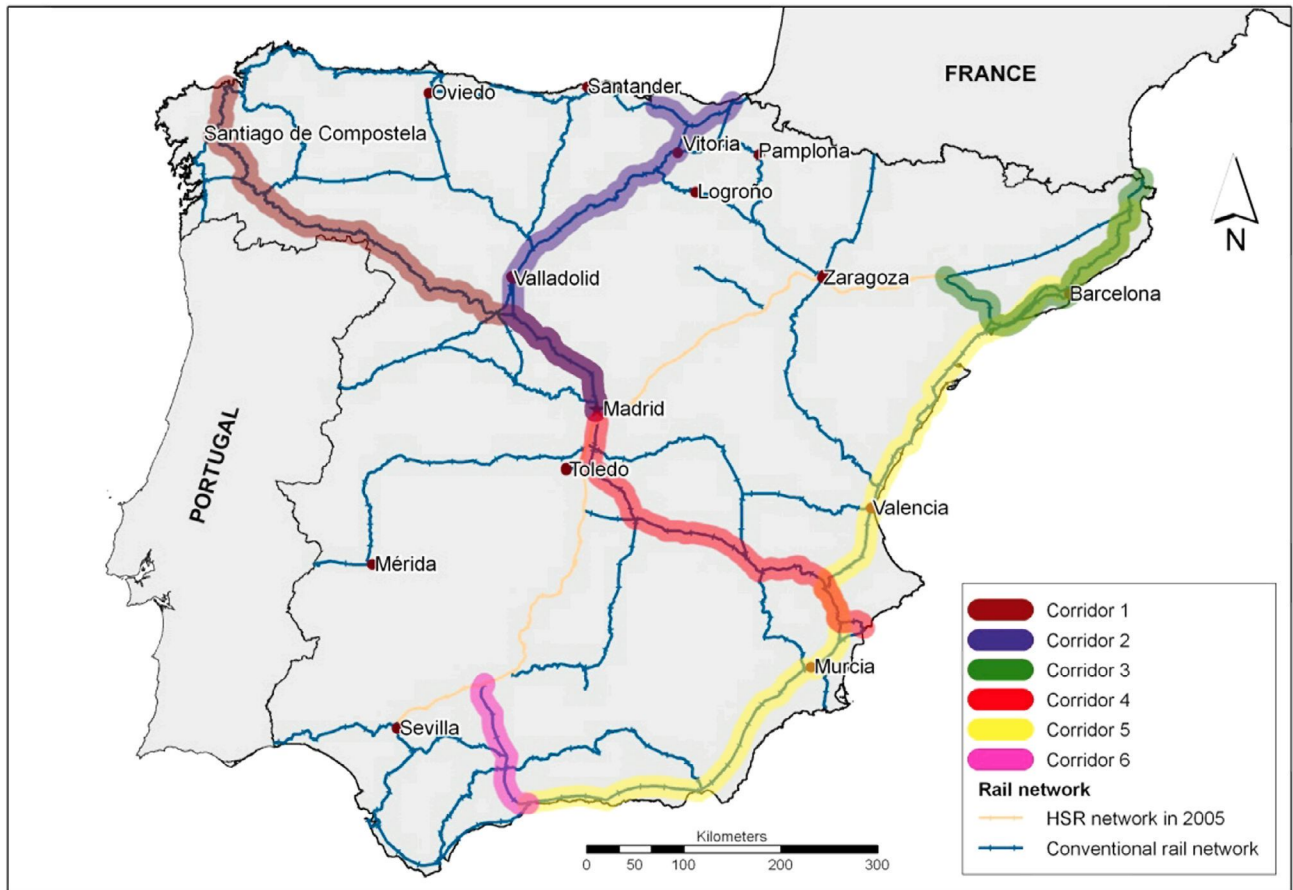


Fig. 3. HSR corridors selected.

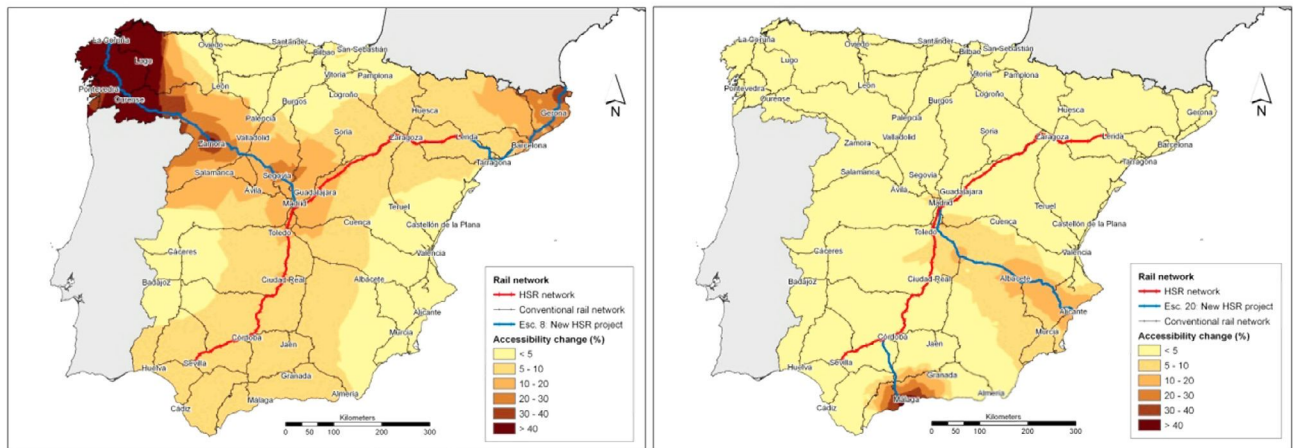


Fig. 4. Improvement in rail accessibility (%) in scenarios 8 and 20.

The connectivity was assessed in each of the scenarios in the case study using Eq. (2). Fig. 5 shows that loss of connectivity is not limited to the area occupied by the infrastructure, and therefore some combinations of corridors have more impact than other combinations with corridors that independently have a greater impact.

According to the results (Table 4), the construction of all the railways planned in the PEIT could imply an 11.6% loss of connectivity between the habitats on the peninsula. The most damaging combinations can be seen clearly – e.g. in the four-corridor

combinations, scenario 45 (corridors 1, 2, 4 and 5) is the most detrimental. It is also evident that there are scenarios that cause a lower connectivity loss than scenarios formed by fewer corridors. Table 4 shows the landscape connectivity loss value, the value per kilometre, the loss in percentage compared to the “do-nothing scenario” and the order within scenarios with the same number of corridors.

The most noteworthy results include the fact that the three-corridor scenario with the greatest impact is scenario 29 (corridors 1, 4 and 5), whereas the corridors that separately cause the greatest

Table 3
Accessibility improvements in a sample of scenarios.

Name	Corridors	Length (km)	Indicator value	Value/km	Improvement (%)	Position according to % ^a	Position according to value/km ^a
esc_1	0 0 0 0 0 1	676.0	67.25	0.006	5.97	1	3
esc_2	0 0 0 0 0 2	552.9	66.25	0.005	4.40	4	4
esc_3	0 0 0 0 0 3	338.5	66.90	0.010	5.41	2	1
esc_8	0 0 0 0 1 3	1,014.5	70.93	0.007	11.76	1	2
esc_13	0 0 0 0 2 4	981.9	68.14	0.005	7.36	13	10
esc_20	0 0 0 0 4 6	577.7	66.20	0.005	4.30	15	11
esc_27	0 0 0 1 3 5	2,106.3	74.44	0.005	17.29	1	11
esc_28	0 0 0 1 3 6	1,163.2	72.31	0.008	13.93	8	1
esc_33	0 0 0 2 3 5	1,983.2	73.28	0.005	15.46	3	12
esc_41	0 0 0 4 5 6	1,669.5	70.25	0.004	10.69	18	20
esc_43	0 0 1 2 3 5	2,659.2	76.83	0.005	21.06	1	11
esc_45	0 0 1 2 4 5	2,749.7	75.83	0.004	19.49	4	15
esc_46	0 0 1 2 4 6	1,806.6	73.06	0.005	15.12	15	7
esc_57	0 1 2 3 4 5	3,088.2	79.45	0.005	25.19	1	4
esc_58	0 1 2 3 4 6	2,145.1	76.89	0.006	21.15	6	3

^a The first scenario in % in its group is shown in bold. The first scenario in value/km in its group is shown in italics.

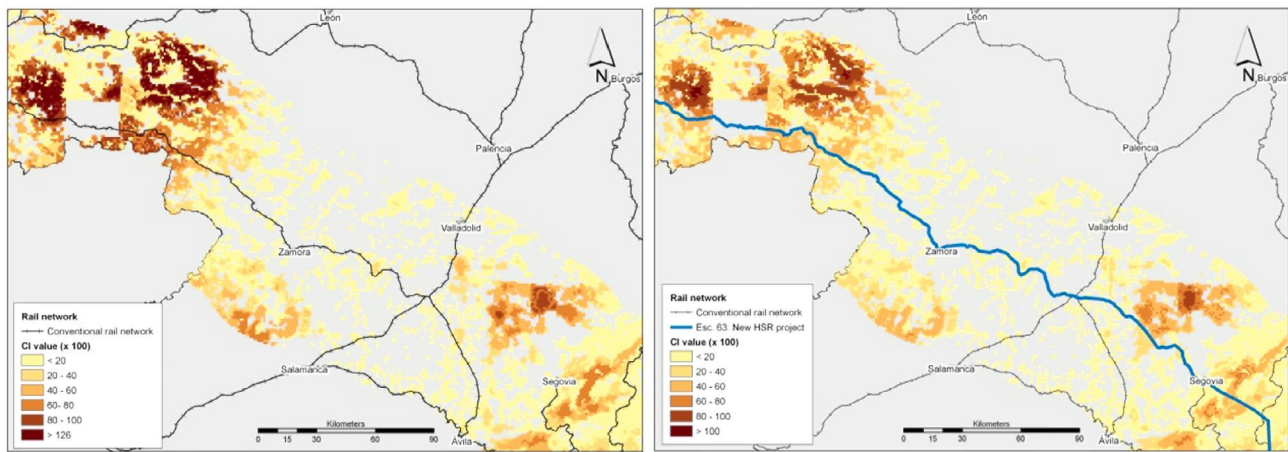


Fig. 5. Detail of connectivity loss due to railway scenario 63.

Table 4
Landscape connectivity loss in a sample of scenarios.

Name	Corridors	Length (km)	Indicator value	Value/km	Loss (%)	Position according to % ^a	Position according value/km ^a
esc_1	0 0 0 0 0 1	676.0	7,941,312	291.4	2.42	1	1
esc_5	0 0 0 0 0 5	1091.8	8,064,635	67.5	0.91	2	5
esc_4	0 0 0 0 0 4	429.0	8,088,504	116.1	0.61	4	2
esc_9	0 0 0 0 1 4	1105.0	7,898,763	216.8	2.94	2	3
esc_10	0 0 0 0 1 5	1767.8	7,867,660	153.1	3.33	1	5
esc_11	0 0 0 0 1 6	824.7	7,937,325	243.7	2.47	5	1
esc_12	0 0 0 0 2 3	891.4	8,051,329	97.6	1.07	9	8
esc_28	0 0 0 1 3 6	1163.2	7,910,582	195.8	2.80	9	1
esc_29	0 0 0 1 4 5	2196.8	7,834,240	138.4	3.74	1	8
esc_38	0 0 0 3 4 5	1859.3	8,018,380	64.5	1.47	15	19
esc_39	0 0 0 3 4 6	916.2	8,057,772	87.9	0.99	20	13
esc_44	0 0 1 2 3 6	1716.1	7,884,680	147.8	3.12	10	3
esc_45	0 0 1 2 4 5	2749.7	7,808,360	120.0	4.05	1	9
esc_46	0 0 1 2 4 6	1806.6	7,868,870	149.1	3.31	9	2
esc_57	0 1 2 3 4 5	3088.2	7,802,740	108.7	4.12	1	4
esc_58	0 1 2 3 4 6	2145.1	7,842,140	138.1	3.64	5	1
esc_59	0 1 2 3 5 6	2807.9	7,834,250	108.3	3.74	4	5

^a The first scenario in % in its group is shown in bold. The first scenario in value/km in its group is shown in italics.

loss are 1, 3 and 5. Significant differences can also be seen for the impact value in percentage or by kilometre.

3.4. Effects on other territorial variables

To calculate the impact on other territorial variables, we selected the effect on landscape, biodiversity and land-use quality. The effects were assessed by calculating the area affected by the

infrastructure and assuming that all the characteristics defining the variable are lost (see Table 2). To determine the impact in the three cases requires a map assessing each one of the three variables.

3.4.1. Landscape quality loss

The map used was the Landscape Quality Map of the Iberian Peninsula and the Balearic Islands (Otero, Mancebo, Ortega, &

Casermeyro, 2007), which assesses the landscape associations defined in the “Atlas of Spanish Landscapes” (Mata & Sanz, 2003) and establishes ten landscape quality classes from 1 (poor quality) to 10 (excellent quality).

The method selected to determine the impact caused by the new infrastructures was the “buffer type”, considering the infrastructure’s zone of influence on the landscape to be 5000 m (Cañas Guerrero, 1995).

The results in Table 5 reveal that when the effects on the landscape are seen as an isolated impact located in an area near the infrastructure, the impact caused by the union of two corridors is the same as the sum of the impacts caused by each one of them individually (with a minor difference due to the possible zones in which both corridors may be connected).

In this case the impact must be analysed by linear km of infrastructure to determine which corridors affect the most valuable areas. It can be seen that some four-corridor scenarios have less impact on the landscape than scenarios with three and even two corridors. Table 5 shows the landscape quality loss value, the value per kilometre, the impact in percentage compared to the “do-nothing scenario”, and the order of the impact in the scenarios with the same number of corridors.

These values highlight the finding that some scenarios have an up to 30% greater impact than other scenarios with the same number of corridors. Another result is that the impact per kilometre is generally similar in all of them.

3.4.2. Biodiversity loss

In order to assess biodiversity, we used the Map of Environmental Quality: Biodiversity (Mancebo Quintana, Ortega Pérez, Martín Ramos, & Otero Pastor, 2007). The map is based on objective variables in purely ecological terms such as land use, habitats and variables that measure biodiversity. It calculates biodiversity as the relation between the degree of naturalness (an abundance measurement) and species richness. This therefore eliminates any subjective components introduced by variables such as perception of the landscape or land quality.

The loss of biodiversity was assessed by calculating the area directly affected by the infrastructure (100 m). However, unlike the case of the landscape, the methodology used to assess biodiversity does not consider solely variables with a specific value, and thus the impact caused is not limited exclusively to the area occupied by the infrastructure.

As with the landscape, the loss of diversity is considered to occur in an area near the infrastructure, hence the impact provoked

by the union of two corridors is the same as the sum of the impacts caused by each one of them separately. The results are similar to those obtained for landscape quality loss in general terms.

3.4.3. Land-use quality loss

It is not easy to identify which land use is superior to another as this is a subjective dimension that depends on the activity in question; in other words, land-use quality will depend on whether it is used for agriculture, forestry, industry... In this case, the variable applied to determine land-use quality was its naturalness; that is to say, the extent to which it is altered by human action. Naturalness is assessed using the Corine Land Cover map of land uses (European environmental agency, 2000), on a scale of 1–10 (Fig. 6).

As with landscape and biodiversity, the loss of land-use quality is considered to occur in an area close to the infrastructure, and thus the impact caused by the union of several corridors is the same as the sum of impacts caused by each one separately.

3.5. Integration of variables

The variables have been integrated to produce a global result for each scenario. The integration module first calculates the impact of all the scenarios as a percentage of the “do-nothing scenario” (Eq. (3)). Then the TITIM GIS-tool makes a multi-attribute aggregation (Eq. (4)). The aggregation is done successively, adding first the environmental variables and then combining their value with the social and economic variables.

The aggregation of the environmental variables distinguishes the variables that rate the ecological features of the territory from those that depend on human perception of the environment. Habitat biodiversity loss and connectivity loss were therefore integrated first, followed by the effect on the landscape. Land-use impact was not considered as it is too isolated and negligible compared to the other impacts within the scope of the plan.

Assuming all the above, the following formulation is used.

Value = $\beta \cdot \text{improvement in accessibility} - \alpha \cdot [\theta \cdot (\delta \cdot \text{loss of biodiversity} + \lambda \cdot \text{loss of connectivity}) + \mu \cdot \text{effect on the landscape}]$ where α , β , θ , δ , λ and μ are weighting coefficients.

Since the aim of this article is not to determine the most appropriate assignment of weights for each variable, the value we assigned assumes environmental and social aspects to be equally important. Ecological features and the effect on the landscape are also considered to have equal importance: $\alpha = \beta = 0.5$; $\theta = \mu = 0.5$; $\delta = \lambda = 0.5$.

Table 5
Landscape quality loss in a sample of scenarios.

Name	Corridors	Length (km)	Indicator value	Value/km	Effect (%)	Position according to % ^a	Position according to value/km ^a
esc_1	0 0 0 0 0 1	676.0	35,165,500	52,020	1.443	2	1
esc_2	0 0 0 0 0 2	552.9	23,631,500	42,741	0.969	3	4
esc_4	0 0 0 0 0 4	429.0	10,690,500	24,920	0.439	5	6
esc_5	0 0 0 0 0 5	1091.8	50,044,500	45,837	2.053	1	2
esc_6	0 0 0 0 0 6	148.7	4,900,470	32,955	0.201	6	5
esc_7	0 0 0 0 1 2	1228.9	53,504,800	43,539	2.195	6	6
esc_8	0 0 0 0 1 3	1014.5	50,330,300	49,611	2.065	7	1
esc_10	0 0 0 0 1 5	1767.8	85,210,100	48,201	3.496	1	3
esc_11	0 0 0 0 1 6	824.7	40,066,000	48,583	1.644	9	2
esc_24	0 0 0 1 2 5	2320.7	103,549,000	44,620	4.248	1	3
esc_25	0 0 0 1 2 6	1377.6	58,405,300	42,396	2.396	14	7
esc_26	0 0 0 1 3 4	1443.5	61,020,800	42,273	2.503	12	8
esc_27	0 0 0 1 3 5	2106.3	88,844,200	42,180	3.645	4	9
esc_28	0 0 0 1 3 6	1163.2	55,230,800	47,482	2.266	15	1
esc_39	0 0 0 3 4 6	916.2	30,755,800	33,569	1.262	20	19
esc_45	0 0 1 2 4 5	2749.7	112,037,000	40,745	4.596	1	6
esc_46	0 0 1 2 4 6	1806.6	69,095,700	38,246	2.835	12	12
esc_47	0 0 1 2 5 6	2469.4	108,405,000	43,899	4.447	2	1

^a The first scenario in % in its group is shown in bold. The first scenario in value/km in its group is shown in italics.

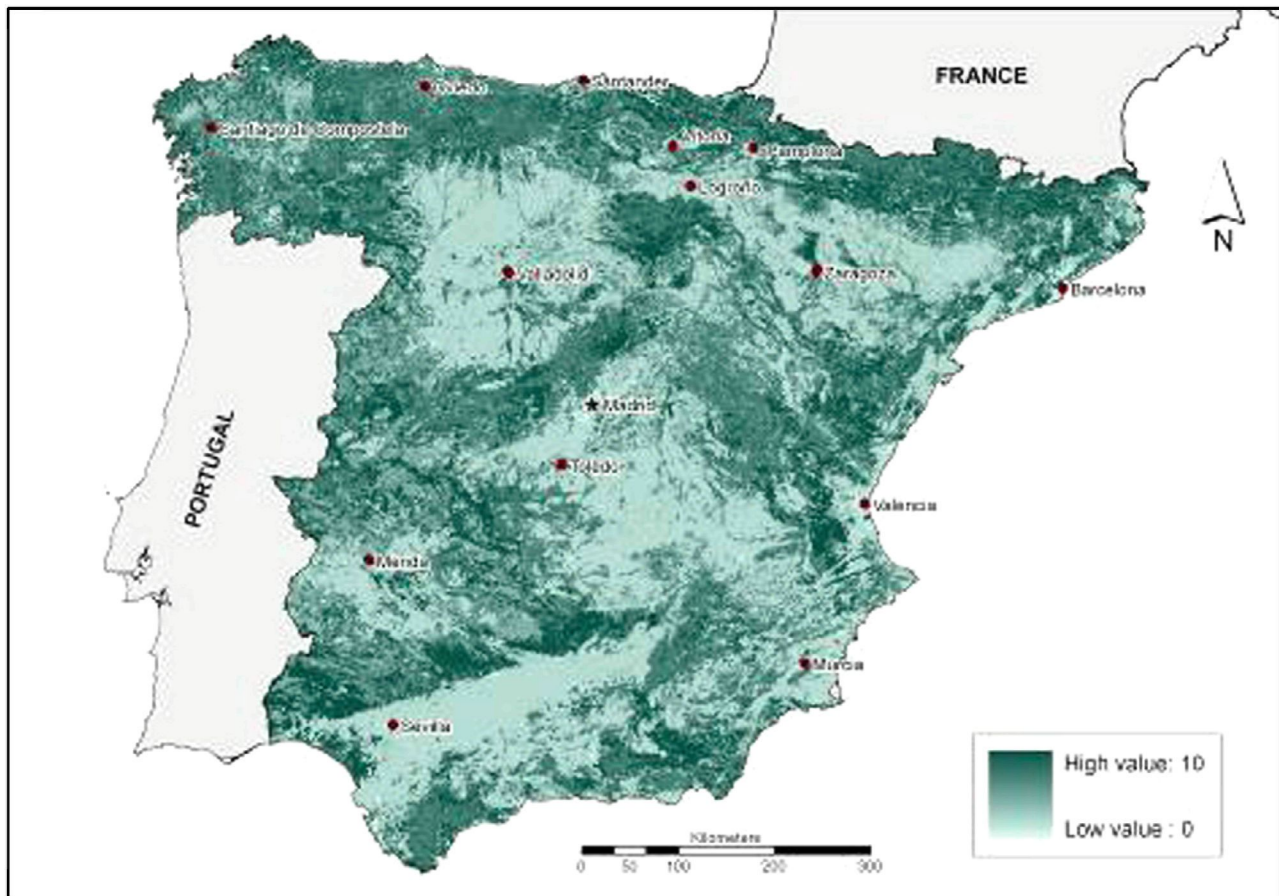


Fig. 6. Map of land-use naturalness.

Table 6
Values after the integration of variables and position.

Name	Corridors	Length (km)	Environmental value	Social value	Total value	Position in its group ^a	Position in the total
esc_1	0 0 0 0 1	676.0	1.33	5.97	1.92	3	58
esc_2	0 0 0 0 2	552.9	0.67	4.40	2.10	1	56
esc_3	0 0 0 0 3	338.5	0.39	5.41	1.94	2	57
esc_12	0 0 0 2 3	891.4	1.07	10.01	4.07	1	38
esc_18	0 0 0 3 6	487.2	0.51	7.46	2.68	13	54
esc_19	0 0 0 4 5	1520.8	1.56	8.54	2.90	9	50
esc_27	0 0 1 3 5	2106.3	2.68	17.29	5.85	2	21
esc_33	0 0 2 3 5	1983.2	2.02	15.46	5.90	1	19
esc_41	0 0 4 5 6	1669.5	1.66	10.69	3.68	19	45
esc_42	0 0 1 2 3 4	1996.4	2.54	18.85	7.02	7	13
esc_43	0 0 1 2 3 5	2659.2	3.14	21.06	7.66	1	7
esc_56	0 0 3 4 5 6	2008.0	1.76	16.24	5.76	14	23
esc_57	0 1 2 3 4 5	3088.2	3.42	25.19	9.16	1	1
esc_61	0 1 3 4 5 6	2684.0	3.07	23.53	8.12	4	4
esc_63	1 2 3 4 5 6	3236.9	3.52	27.82	10.08		

^a The first scenario in its group is shown in bold.

Table 6 shows a selection of the results obtained after integration according to the coefficients used. It also shows the position of each scenario in its group (same number of corridors) and in the total.

In general terms the table shows that according to the criterion selected, the socio-economic benefit generated by the new corridors is very high and the negative environmental impact they cause is low in comparison. The corridor generating the greatest socio-economic benefit and with the least impact is corridor 2. If the corridors are gradually added, the first is corridor 3, then corridor 5, then 1 and finally corridor 4.

Another significant finding is the fact that corridor 1 produces the greatest improvement in accessibility, although its high environmental impact makes it unadvisable to proceed with its construction.

4. Conclusions

This article presents a DSS to assess the territorial effects of new linear transport infrastructures based on the use of GIS. The TITIM – Transport Infrastructure Territorial Impact Measurement – GIS tool allows these effects to be calculated by evaluating the

improvement in accessibility, loss of landscape connectivity, and the impact on other local territorial variables such as landscape quality, biodiversity and land-use quality. This assessment gives an overall view of the environmental, social and economic implications of a transport infrastructure or a transport infrastructure plan. This research supplies a unique DSS to correct the lack of modelling tools that integrate both accessibility and territorial environmental impacts in transportation planning.

Due to the large number of processes required, the use of fully-developed GIS DSS considerably facilitates the work. The TITIM GIS tool assesses these variables automatically, simply by entering the required inputs, and thus avoiding the manual reiteration and execution of these multiple processes. This substantially reduces both possible calculation errors and the estimated time, and particularly when preparing the database stages before calculating the indicators. By programming the methodological calculation procedure in a language suitable for GIS, it is possible to manage the huge databases required at the national/planning level. The processes are faster and the visualisation time is eliminated. As an example, tables with 65,600,000 rows can be managed to calculate the accessibility for 8100 origins in Spain. For habitat connectivity loss, it can handle the Spanish habitat map (DGBIO, 2005), containing 165,000 polygons. In addition, TITIM allows researchers to use their own GIS databases as inputs, in contrast with other tools that use official or predefined maps (Enei et al., 2012; Herrero-Jiménez, 2012).

The application to the case study demonstrates the usefulness of the TITIM GIS-tool for planning infrastructures for the following reasons: it allows a large combination of alternatives to be generated for assessment; it enables the comparison of alternatives; and it can be used to establish an order of priority based on the benefit obtained from the available resources. The indicators in this study make it possible to assess the impact of the new infrastructure on the whole of the transport network (accessibility improvements) and on nature areas in a wider territory (connectivity loss), not restricted to the individual project, as recommended in the application of the EAE.

The results show that the percentages of accessibility improvement caused by the various scenarios differ widely. As the number of corridors increases, these differences between scenarios are reduced, as the effects of the corridors in the scenarios are offset. Connectivity loss is not limited to the area occupied by the infrastructure, and thus certain combinations of corridors have a greater impact than other combinations with corridors with more impact when considered independently. The loss of landscape quality, land-use quality and biodiversity occurs in an area near the infrastructure. The integration of impact values into a single value is a convenient method of comparing scenarios depending on the policy established, prioritising either socio-economic benefits or the preservation of the environment.

Issues for future research include the introduction of the estimation of consumptions, emissions and pollutants, as occurs in others DSS (Sobrinho et al., 2014), in order to consider not only territorial impacts. Construction costs (Kim et al., 2014) also need to be considered. Another especially relevant aspect involves the incorporation of other methods of integrating the variables, as used in Coutinho-Rodrigues et al. (2011). Finally, the scripts can be modified in order to introduce improvements. Although TITIM can be used with any researcher's GIS databases, these databases need to meet certain conditions; thus a further improvement would be to increase its flexibility.

Acknowledgement

The authors would like to thank the anonymous comments of the reviewers for the improvement of this work.

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